Forum for Electromagnetic Research Methods and Application Technologies (FERMAT)

Evolution of Frequency Selective Surfaces

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Abstract— **This review gives an account of the route through which Frequency Selective Surfaces have developed in form and in application over the past few decades. Applications range from their use in radome structures, and in meta-materials, to their incorporation into buildings for signal propagation control in the built environment. For some of these applications the geometries of the array elements can be very simple, but in cases where surfaces are curved, significantly more complicated configurations are likely to be required. Fabrication cost is an important issue. In applications to multiband radiometry for satellite systems for example, the high cost of precision manufacture is normally considered to be acceptable. In contrast, in the built environment inexpensive larger scale production techniques are important. Inkjet or 3D printing may offer cost effective ways forward.**

Index Terms— **Frequency Selective Surfaces, Additive manufacturing, 3D printing, Electromagnetic Wave Propagation, Electromagnetic Architecture, Metamaterials, Radar Absorbent Materials, Antennas.**

I. INTRODUCTION

Frequency Selective Surfaces (FSS) have been around a long time, easily over 50 years if not longer. Probably the best introduction and practical design guide is by Ben Munk [1] which contains some history. For those interested in computational methods, an early review by Raj Mittra et al. [2] is recommended. With the recent interest in meta-materials it is perhaps timely to consider a current list of applications of FSS and of areas where new engineering solutions and further research work would be of special value.

So how should we define an FSS? Pedantically, a single FSS should be a thin surface defined by a pattern of conductor or resistive material on a generally curved surface with some structural support, usually a dielectric layer. Of course multiple FSS structures may be, and often are, constructed using multiple dielectric layers and/or FSS embedded within some composite. In addition, an FSS may also feature non-thin components such as inductors, capacitors, diodes and transistors which are bonded to the surface. Often these are referred to as circuit analogue structures. The FSS may feature deliberate loss, as part of a radar absorbing material, or may be designed to be as lossless as possible. They may be active, featuring amplification structures, semi-active featuring biased diodes etc. or completely passive. There may be connecting structures, such as vias, between FSS or each FSS may be electrically isolated. They may also comprise arrays of fully three dimensional elements, such as the calthrops described later. It soon becomes difficult to decide what to call such structures and how they fit in with antenna array definitions, two or three dimensional meta-materials, dichroic surfaces, etc.

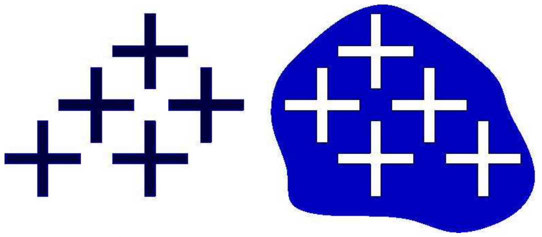
Another set of issues are associated with design tools. Full wave analysis methods are far more common today than they were 25 years ago and 50 years ago they were almost non-existent except for special geometries. Nowadays it is difficult to keep track of new methods and several general purpose commercial software packages are available providing high accuracy and reliability. It still remains the case, however, that periodic surfaces are the most easily analyzed, where the structure is defined by a unit cell whose dimensions are not large compared to a wavelength. Such periodic surfaces strictly require a global unit cell which both restricts the nature of the curved surface and the nature of the interactions between FSS if the FSS do not share a common periodicity. In practice, approximate methods are often of more engineering value for realistic engineering problems. For example, it is common practice to analyze structures with slow changes in curvature using methods related to physical optics (PO) where the FSS is assumed to behave locally as if its reflection and transmission characteristics are as defined using an infinite tangent plane analysis. Software such as GRASP [3] permits large structure analysis with FSS data supplied in this form.

For those structures designed to be lossless, typically for radome designs, transmission losses are a problem. These can be much greater than basic theory would suggest and can prevent the use of FSS for some applications. For example a high-Q band-pass FSS with 3dB 10% bandwidth may show a measured transmission loss of between 1 and 2 dB on a low loss substrate where theory might indicate a small fraction of a dB. There are several sources of loss, some ohmic and some not. FSS structures invariably concentrate electric currents and electric fields in regions of the geometry where the dielectric support structure may be badly defined. In general dielectric values and loss tangents are specified in an average sense but in reality dielectric materials are composite containing bonding layers, material inclusions and other scale-dependent structures. Concentrating fields over small regions in space implies that the average dielectric and loss tangent values may not be appropriate. Surface roughness, on the conductor dielectric interface, plays a role in this and can be important at surprisingly low frequencies, well below 10 GHz. Non-ohmic losses feature the scattering of energy in non-specular directions which can be especially important in curved structures. There are many mechanisms which may be responsible, including the radiation of energy by surface and trapped waves and non-uniformities in the dielectric substrate thickness and lateral variations in the dielectric constant. Disentangling all these effects is difficult.

Finally, there are the engineering and cost issues. Often FSS are limited by the precision in which they can be etched and may be required over large areas of surface. There are also difficulties, both theoretical and practical, of design and construction of FSS composites over doubly-curved surfaces. The concept of periodicity on a general curved surface does not exist in an ordinary sense leading to the question of how the pattern on a doubly curved FSS should be best defined. There are local cut-and-paste methods as well as global projection methods, each of which may be used as the basis of a mathematical definition as well as a means for practical construction. The former methods, e.g. [4], have more in keeping with the infinite tangent plane approximation, but lead to local discontinuities in the pattern periodicity. The latter can avoid discontinuities but give rise to significant local distortions. This is a recognized long standing problem which deserves attention at a fundamental level. Fast general purpose numerical methods which guarantee accuracy do not exist although many approximate methods have been developed which have been shown to be accurate and efficient for special classes of structure (e.g. [5]). Ray tracing approaches have also been explored, e.g. [6]. At the practical level cheap manufacture requires the processing of two dimensional flat materials using print and etch technologies. Thin flat materials can be wrapped around surfaces of single curvature but not doubly curved surfaces without introducing cut-and-paste distortions. The electrical effect of these distortions is sometimes acceptable but not always. 3D print technologies may offer an alternative cost effective method (Section X).

II. SLOT STRUCTURES AND ELEMENT STRUCTURES

Often an FSS or multiple FSS composite is required with a band-pass or band-stop characteristic. A single FSS with band-pass nature is topologically of slot form, where in the low frequency limit the surface is indistinguishable from a uniform perfect conductor. A single FSS with band-stop nature is topologically of dipole element form where, in the low frequency limit the surface is invisible. Perfectly conducting slot structures feature perfect electrical connections between contiguous unit cells. Conversely, dipole element structures are characterized by structures which are not connected across unit cells. The definitions apply for both single and orthogonal dual polarization use with suitable attention given to the directions of current flow across cell boundaries. For a single (thin) perfectly conducting FSS, the dipole element and slot characteristics are dual and are related by Babinet complementarity. This is only approximately true when the FSS are supported by a dielectric substrate and not true when there are multiple FSS present [1].



Perfectly conducting elements. Slots in perfect conductor.

Fig.1 Babinet complements of elements and slots

III. EQUIVALENT CIRCUIT THEORY

The use of equivalent circuit theory to represent the characteristics of FSS goes back to the origins of FSS, fifty or so years ago when full wave analysis was difficult to carry out except for the simplest structures. Quasi-static analysis may be used to represent a lossless FSS by a surface impedance characterized by a simple arrangement of inductors (L) and capacitors (C). Resistors (R) are incorporated for lossy structures. Often such analysis was applied to FSS in rectangular waveguide where there is a one-to-one correspondence between the exact solution of a rectangular lattice in free space and that within the guide [7]. Accuracy is generally good up to and slightly beyond the first FSS resonance.

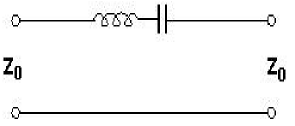


Fig.2 Simplest equivalent circuit representation of a band pass FSS in free space corresponding to a slot structure for one polarisation and incidence angle.

Equivalent circuit theory can provide useful physical insight, provide interpolation of transmission and reflection coefficients as a function of frequency and also provide methods of synthesis. This is because the response of an equivalent circuit is by definition a realizable function of frequency and there exists a well-established body of theory on the use of equivalent circuits in control theory, filter theory and circuit synthesis [8]. It may also be used in RAM design (see below) for the same reasons. However, for all but the simplest circuits, equivalent circuits are not generally unique and it may be necessary to switch between topologies depending on some external parameter if the LCR values are to remain all positive. Thus, one equivalent circuit may be good for a range of angles of incidence (with capacitors, inductors and resistors that change value with angle of incidence) but may need to be switched to another representation outside of this range. How this should best be done appears to be an area where there is little theory available and would be an interesting topic of further investigation.

IV. NON-PERIODIC STRUCTURES

Most FSS applications assume structures which are periodic and defined by a unit cell that repeats indefinitely. However there are several areas of practical interest for which this is not true. Furthermore there are many types of non-periodicity. There is non-periodicity intrinsic to the use of curved surfaces, of the kind discussed in the introduction, and there are the random variations in geometry and constitutive properties that can occur on an infinite flat surface. For example a single FSS may exhibit a randomness with unit cell dimensions or element dimensions or loadings that are modulated by a random function as a function of spatial coordinates. If the modulation is small enough and the FSS topology is maintained, experimental evidence shows that the dominant effect is to broaden out the FSS resonance and an incident plane wave is scattered into a continuous distribution of angles around the specular direction. Such randomness may be used to model random lateral changes in the dielectric constant of the substrate or to model the effect of manufacturing processes.

Another kind of non-periodicity is associated with the use of multiple FSS. It is possible for two or more FSS to be individually periodic but not to share a common periodicity. If the FSS are separated by a distance large compared to their individual unit cell dimensions then the FSS structure can be accurately analyzed without evanescent wave coupling between surfaces, based on their individual periodicities. However, when the FSS become tightly bound, it becomes necessary to consider the global unit cell, rather than the individual ones, and there may not be an exact finite global unit cell. What approximation rules can be adopted in these circumstances? It is possible that these sorts of closely coupled structures might permit control of grating lobes with new antenna possibilities, or effects may invariably be undesirable.

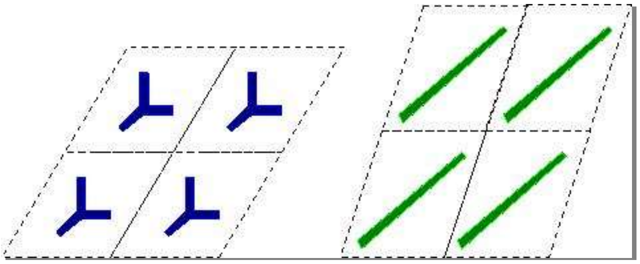


Fig.3 Cells shown of two infinite FSS not sharing a common periodicity

V. NON-RECIPROCAL STRUCTURES

Non-reciprocal structures offer the possibility of direction-dependent screening. For example a high radar cross section antenna used in a single receive or transmit mode might be screened *over the operational frequency band of the antenna,* not just outside the band as described below. There are two types of structure we are aware of. One sort features the use of amplifiers (active semiconductors) with an amplifier on each unit cell. A structure of this kind might feature a "receive" FSS which feeds the signal in each unit cell through an amplifier to a "transmit" FSS. The entire structure is planar with thickness similar to or larger than a unit cell and may be considered as an antenna array repeater. These devices work and we have achieved such structures with amplifier gains of at least 20 dB with no signs of instability. Another type of structure features passive non-reciprocal elements such as ferrite isolators. Such elements may be integrated onto a single FSS or constructed using two FSS with a design similar to the active repeaters just described. Problems with active structures are those common to active antenna arrays including cost, fabrication difficulties on curved surfaces, power handling and low noise requirements. There are similar problems with passive structures though noise is replaced by loss as a figure of merit. There are often difficulties obtaining sufficiently small components.

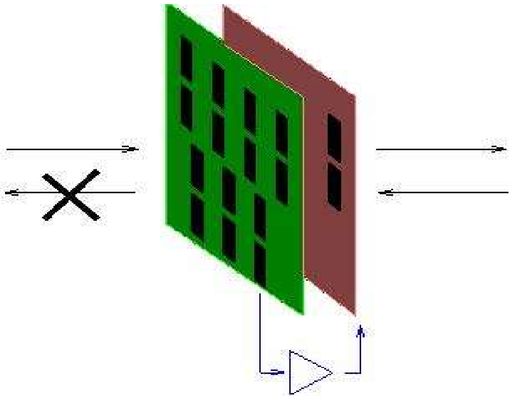


Fig.4 Non reciprocal elements, such as amplifiers, prevent waves propagating in reverse direction

VI. RADOME AND REFLECTOR ANTENNA APPLICATIONS

Some of the earliest applications of FSS involved the design of radomes and sub-reflectors for reflector antennas. Early work of the former tended to be, and may still be, of a classified nature since this has a bearing on stealth technology. A problem in the design of vehicles with small radar cross section (RCS) was, and still remains, the RCS contribution of antennas. With the possible exception of conformal phased arrays, which are costly and share some of the design problems of FSS, electrically large antennas have large RCS. To reduce this, at least over the frequency range outside the operational band of the antenna, it is possible to shroud the antenna by a radome which reflects or absorbs. This requires an FSS radome which is transparent in-band and reflective (or possibly absorptive) out of band.

Similarly, high performance multi-band reflector antennas require a shared aperture over different frequency bands. Because of the difficulty in designing UWB feeds with the necessary beam widths sub-reflectors may be designed to reflect one band and pass another, so that different feeds covering different frequencies may be located at different places.

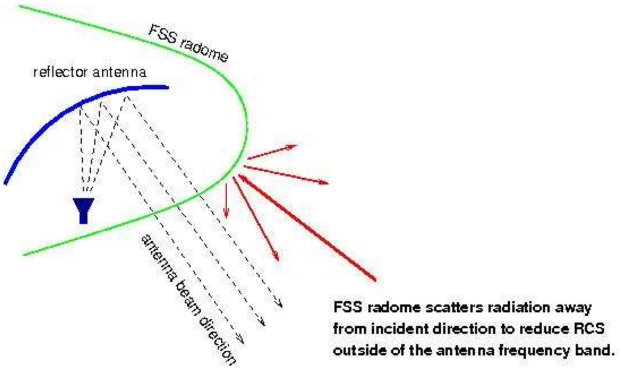


Fig.5 Reflector antenna shielded by an FSS radome

Under standard Fourier wave theory, the illumination of a finite shaped radome or reflector by a plane wave may be represented as a superposition of TE and TM plane waves of infinite extent propagating in different directions. Thus, it is not enough to design an FSS which has a pass band at one angle of incidence; it is required to design an FSS with a common pass band over a range of angles of incidence and over both polarization types. Angle insensitivity of FSS filter characteristics is an important design requirement and is difficult to achieve. One approach is to design the FSS using a unit cell size which is small compared with a wavelength at the FSS pass frequency. Not only does this push away the onset of the first grating lobe frequency but the FSS begins to adopt quasi-static characteristics. Significant reduction in unit cell size can be accomplished using convoluted elements [9], [10]. Insertion of lumped reactive elements into the unit cell is another miniaturization technique [11]. When the unit cell size is small, there are intuitive grounds for believing that an FSS can be represented by a uniform surface impedance which is independent of angle of incidence and certain sorts of convoluted element small unit cell structures can achieve high angular stability. However, it may not be true for structures featuring a rapid change of surface impedance with frequency, i.e. for sharply resonant structures with small fractional bandwidths. No proof appears to be available showing under what conditions the (angle of incidence independent) impedance approximation is valid.

Angular stability may also be achieved with relatively large unit cells, small but not very small compared to a wavelength. Single FSS loop structures [1] are an example of such, commonly circular or hexagonal loops. These are relatively simple to analyse and may be manufactured with less control over geometric tolerances. Sometimes compensation can be achieved using multiple FSS structures. For a few applications, narrow band pass band characteristics are required, also with a common pass band with respect to angle of incidence. This can be achieved using convoluted structures or tightly coupled multiple slot arrays e.g. using two arrays of rectangular offset slots whose inter-FSS separation distance is much smaller than a unit cell dimension [12], [13].

Another difficulty with thin FSS structures is that the TE and TM characteristics are usually quite different as a function of angle of incidence, whether or not there is a common overlap region in the transmission coefficient. Under the constant surface impedance approximation, taken as valid when a unit cell is small compared to a wavelength, the bandwidth is proportional to the cosine and reciprocal cosine of the angle of incidence for the TE and TM polarized waves. Although partial compensation methods are available using multiple layers, obtaining a transmission or reflection characteristic as a function of frequency that is independent of both angle of incidence and polarization is very difficult. One possible solution lies with the use of fully three dimensional elements, as described later.

VII. RADAR ABSORBENT MATERIAL APPLICTIONS

The design of light-weight conductor backed thin radar absorbers capable of operation over large bandwidth and at low frequencies remains a fundamentally difficult topic much of which remains classified. However, there exists a body of unclassified work showing that there is a fundamental limit on achievable bandwidth related to electrical thickness at the lowest frequency of operation and the relative magnetic permeability at zero frequency. Rozanov [14] is usually credited with this work though the authors are aware of similar concurrent classified work undertaken in the UK (RSRE, UK MoD, 1998-1999). The fundamental performance limit is achieved if and only if the composite RAM, assumed passive, shows minimum reflection phase. If the free space impedance is Z_0 and the input impedance of the RAM to a plane wave is designated as a rational function P(p)/Q(p) with polynomials P(p) and Q(p) as a function of the Laplace transform variable p, then at normal incidence this requires that $P(p)-Z_0Q(p)$ be a Hurwitz-stable polynomial. No amount of "tinkering" using passive inhomogeneous, artificial magnetic or meta-materials can violate this limit though some improvements can be accomplished using active materials [15]. In general it is necessary not only to achieve some specified reflection loss characteristic but also ensure that the structure exhibits minimum reflection phase for maximum efficiency. The bound depends on the polarization and angle of incidence [16], as does the reflection coefficient so achieving both the bound and a specified reflection coefficient function is usually very hard. It is almost impossible if the RAM contains magnetic materials since the relative permeability of magnetic materials at zero frequency is usually orders of magnitude larger than at microwave frequencies. One method by which the integral performance bound can be improved (bounded by the theoretical limit) while retaining a useful reflection characteristic is by the incorporation of FSS within the (lossy) composite [16].

VIII. META-MATERIALS AND META-SURFACE APPLICATIONS

The design of artificial dielectrics goes back well before the term "meta-material" was coined but it is now common to refer to all such materials as meta-materials. There has been a recent resurgence of interest, partially as a result of fictional and in the authors' opinion, infeasible, invisibility devices. However, there are a number of current and potential applications where meta-materials and some of the new design methods featuring transformation electromagnetics may be of significant industrial value.

FSS may be incorporated in the design of three dimensional meta-materials; materials characterized by a scale and frequency dependent relative permittivity and permeability tensor. Examples include the design of materials with perfect magnetic boundaries, negative relative permittivity and permeability, etc. All such exotic structures have special dispersion requirements to be realizable and fundamental bandwidth limits.

Typically FSS for these applications are designed to be periodic with a unit cell small compared to the operational wavelength. When such FSS are considered stand-alone or part of a simple dielectric composite they are sometimes termed meta-surfaces and the tensor valued surface impedances that describe the electrical properties of such surfaces share many of the same transformation laws that describe the relative permittivity and permeability tensors in three dimensions.

There has been a recent convergence of mathematical methods and technologies that are leading to many more applications of meta-materials and consequently to FSS. On the mathematical front, there is the recent field of transformation electromagnetics which permits the design of wave devices of all kinds *provided* suitable anisotropic materials with the necessary relative permittivity and permeability tensors can be constructed. Modifications of these methods are becoming available which place constraints on the tensors so that achievability is more practical, although much more work is still required.

One of the biggest current problems in meta-material design is that the materials are usually required to operate near resonance and are thus strongly dependent on frequency. This means that operational fractional bandwidths are usually quite small, typically less than ten percent. At a fundamental level this is because it is not possible to obtain an impedance function defined as an arbitrary function of frequency. Causality and energy conservation place strict limits on what is achievable. This also explains why loss is such an important issue [17]. As an aside we would remark that, while there is a fair body of literature on the causal limitations of scalar valued materials with scalar and causally independent values of relative permittivity and permeability, there is very little theory on the limitations of tensor valued materials, especially when the principal axes are frequency dependent or where the relative permeability and permittivity on the macro-scale are coupled through Maxwell's equations on the micro-scale.

However, there are many applications where fundamental realisability is not thought to be an issue. Indeed, some designs seek to deliberately use materials that are far from resonance resulting in the ability to design broadband structures. Using currently available materials at frequencies significantly greater than 1 GHz, this generally means materials with close to unity relative permeability and ones with relative permittivity or surface impedance that varies little with frequency.

On the engineering front there are new fabrication methods being developed. Application of FSS in situations such as the built environment, for the control of wave propagation within, or into, buildings requires inexpensive fabrication techniques – the cost of the final product must not be inconsistent with the cost of other building components if at all possible. Low-cost manufacture contrasts with the requirements of, for example, aerospace systems, where quantities might be relatively small but where high precision fabrication of critical components is essential, and usually involves costly specialized materials. Fabrication errors are more likely to occur as costs are reduced. Recent studies suggest that defects in more than 10% of the array elements can be tolerated in the built environment scenario [18]. Ink jet printing is one possible route to reducing costs. But an alternative is the use of 3D printers [19]. These provide cost effective ways for rapid prototyping and for constructing objects whose constitutive parameters vary in a prescribed manner as a function of position.

IX. 3D ELEMENTS IN FREQUENCY SELECTIVE SURFACES

The use of periodic structures containing three dimensional elements is becoming a topic of some interest. Such structures permit the flow of electric currents with components perpendicular to the surface and can provide a level of control of both the local electric and magnetic fields that cannot be achieved using single-surface current distributions. This permits the engineering of meta-materials with effective non-unity relative permeability, bianisotropic materials (e.g. using helical structures) and FSS materials with less sensitivity to angle of incidence. It is worth remarking that, at least in theory, materials with similar properties can also be created using multiple layer FSS with strong evanescent coupling of fields between layers. Essentially, we may synthesize 3D structures from multiple 2D structures strongly coupled by capacitive or inductive near fields [17]. This may provide some advantages on curved structures, where the laying up of multiple thin surfaces within a non-flat substrate can be easier and cheaper than the embedding of three dimensional elements. However, relatively little work has been done in this area.

Many examples of 3D structures exist. The calthrop structures presented in section X provide a frequency response which is fairly insensitive to both angle of incidence and polarization [20] and may be fabricated using cheap 3D print technologies. The demonstration of meta-materials with negative refractive index has been attempted using split annulus structures in 3D configurations. Artificial magnetic boundary materials (with bandwidths greater than can be achieved using simple dielectric layers) commonly use conducting vias. All of these employ current flows normal to the surface and can be regarded as three dimensional. Recent advances have also been made using three dimensional transmission line elements [21], [22] to provide quasi-elliptical filter characteristics.

X. 3D Printing of Frequency Selective Surfaces

Additive manufacturing enables complex objects to be made from a digital model, by laying down successive layers of different shapes. An illustration is the extension of the tripole element by adding one more arm (Fig. 6) to form a calthrop [20], and fabricated with a printer that utilized the fuse filament fabrication (FFF) process. The input material was a plastic.

An illustration of the structure is shown in Fig.7. When placed as a two dimensional FSS array, the most compact configuration is a triangular lattice with one arm perpendicular to the plane. It this case, it offers symmetry in three planes each at 120° from each other.

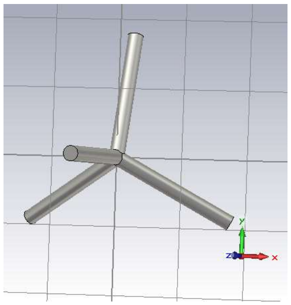


Fig.6 Three-dimensional view of the tetrahedral calthrop

As expected for this type of structure, the transmission response proved to be very stable to angle of illumination.

The digital design was exported to slicing software which took the 3D drawing and translated the model into individual layers. The machine employed was the Mbot3D printer, and is shown in a separate video clip. The printed structures were then coated with a layer of silver conductive paint applied, in this illustration, by hand. The transmission responses at normal incidence, TE45 and TM45 when the E-field was in the yz plane (Fig. 6) is shown Fig. 8. The FSS resonated at an arm length of L = 0.32λ, with good angular stability and similar behavior in both polarizations.

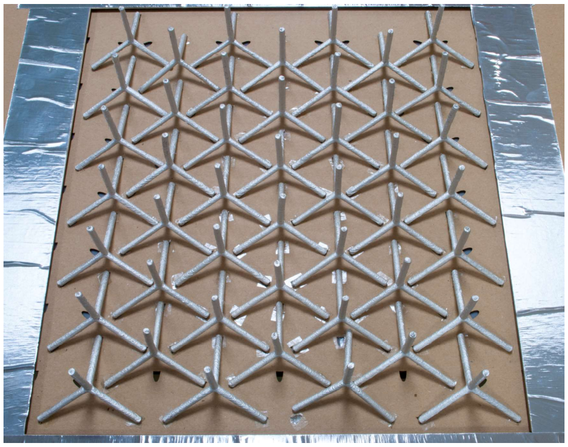


Fig.7 The calthrop array

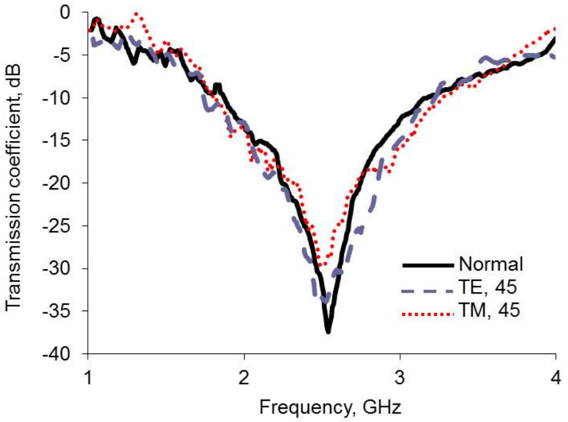


Fig.8. Measured transmission response, incident E-field in the yz plane

X Conclusion and Discussion

FSS have a long pedigree and are used for a number of applications including antenna reflectors, radomes, radar absorbent materials and composite metamaterials. There are many well established design tools and the theory is well developed although there remain a significant number of problem areas of practical and theoretical interest, such as the design and construction of FSS on doubly curved surfaces and the effect of non-periodicity. There are exciting new fronts developing for their use within metamaterials where the use of three dimensional structures, tight coupling between FSS layers and/or the flow of electric currents perpendicular to surfaces using conducting vias is key to controlling the effective permittivity and permeability tensors of the materials.

It is hoped that this review provides a useful perspective. We believe we have reached a point where advances in affordable 3D print technology, established design software and new mathematical methods can now provide an economic way forward for the design and fabrication of new types of structure with many useful properties.

3D printer forming caltrop FSS element, University of Kent UK

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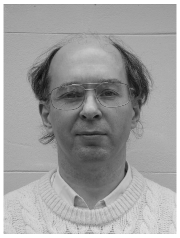

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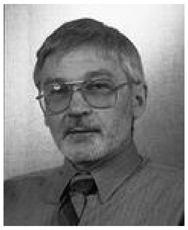

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